Appendix B

Determination of Actual Snow-Covered Area using Landsat TM and Digital Elevation Model Data in Glacier National Park, Montana

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ABSTRACT

In the future, data from the Moderate Resolution Imaging Spectroradiometer (MODIS) will be employed to map snow in an automated environment at a resolution of 250 m to 1 km. Using Landsat Thematic Mapper (TM) data, an algorithm, SNOMAP, has been developed to map snow-covered area. This algorithm will be used, with appropriate modification for differing spectral bands, etc., with MODIS data following the launch of the first Earth Observing System (EOS) platform in 1998. SNOMAP has been shown to be successful in mapping snow in a variety of areas using TM data. However, significant errors may be present in mountainous areas due to effects of topography. To increase the accuracy of mapping global snow-covered area in the future using MODIS data, digital elevation model (DEM) data have been registered to TM data for parts of Glacier National Park, Montana so that snow cover on mountain slopes can be mapped. In this paper, we show that the use of DEM data registered to TM data increases the accuracy of mapping snow-covered area. Using SNOMAP on a subscene within the 14 March 1991 TM scene of northwestern Montana, 215 km2 of snow is mapped when TM data are used alone to map the snow cover. We show that about 1062 km2 of snow are actually present as measured when the TM and DEM data are registered. Approximately 5 times more snow is present when the effects of topography are considered for this subscene, which is in a rugged area in Glacier National Park. A simple model has been developed to determine the relationship between terrain relief and the amount of correction that must be applied to map actual snow-covered area in Glacier National Park using satellite data alone.

Introduction

Snow cover has been mapped at the hemispheric scale for climatological studies (e.g. Matson and Wiesnet 1981; Matson and others 1986; Chang and others 1987), and at the river-basin scale for operational needs (Carroll 1990; Rango 1993). Not only is the amount of snow cover important, but the distribution of snow at different elevations is important to vegetation distribution and animal habitats (Allen and Walsh 1993). It is also necessary to know the elevation of snow cover for areas that rely on snow as a freshwater source, because snowmelt at higher elevations is delayed, relative to snowmelt at lower elevations, thus affecting the timing of runoff.

The advent of the Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, to be flown on-board the EOS platform, beginning in 1998, will permit automated mapping of global snow-covered area from space and determination of snowpack energy-balance components. The MODIS sensor (Salomonson and Toll 1991) should enable improved mapping of global snow cover relative to what is available today. This is because the MODIS will have 36 spectral bands and spatial resolution ranging from 250 m to 1 km.

Current efforts are concerned with the development and testing of an algorithm that will be usable with MODIS data in the future, and determination of errors associated with snow mapping using thematic mapper (TM) data as a surrogate for MODIS data (Hall and others in press). TM data are currently being used to develop the prototype algorithm because the TM sensor has spectral bands in approximately the same locations as some bands on the future MODIS sensor.

In this paper we focus on Landsat TM and digital elevation model (DEM) data of Glacier National Park, Montana, U.S.A. In Glacier National Park, the topography is so rugged that only some of the snow cover is accounted for when using conventional satellite data alone to map snow cover. This is because much of the snow on mountain slopes cannot be mapped using satellite data alone because certain geometric characteristics are sacrificed when a 3-dimensional geoid is projected onto a 2-dimensional map surface.

Efforts to map snow cover by elevation zone using a combination of satellite and DEM data have been successful and result in determination of percent snow cover by elevation zone (Carroll 1990). For this study, we calculate the actual amount of snow (in km2 instead of percent of area covered) in a Landsat TM scene covering Glacier National Park, and discuss the errors caused by topography that are inherent in satellite snow mapping. Actual snow cover in km2 may be used for inclusion into physically-based hydrological and flood-forecast models that require actual surface area of snow cover rather than percent snow-covered area. The technique reported herein is a very simple way to map actual snow-covered area in mountainous regions and applies not only to snow-cover mapping, but to mapping all surface covers by remote sensing in mountainous areas.

Background

A record of snow cover has been acquired since 1966 using NOAA Advanced Very High Resolution Radiometer (AVHRR) and predecessor instruments (Matson and Wiesnet, 1981). Snow maps of the Northern Hemisphere are produced weekly, but production of the maps is not fully automated at this time, requiring an analyst to delineate snow cover manually (Matson and others 1986; Matson 1991; Robinson and others 1993) before the maps are digitized. This record will be continued with the AVHRR sensor on the NOAA-K satellite to be launched in 1996. The NOAA-K sensor will have a 1.6 mm band that will facilitate snow/cloud discrimination - a difficult, if not impossible task, using current and previous AVHRR sensors.

The National Operational Hydrologic Remote Sensing Center (NOHRSC) of the National Weather Service employs both airborne and satellite data to produce real time and weekly snow-cover products for North America during the snow-mapping season. Regional snow products, with 1-km resolution, are produced operationally in about 4000 drainage basins in North America (Carroll 1990; Rango 1993). The Landsat multispectral scanner (MSS) and TM data, with 80-m and 30-m resolution, respectively, are useful for measurement of snow-covered area over drainage basins and thus for use in snowmelt-runoff models to predict snowmelt (Rango and Martinec 1982). The NOHRSC snow-cover data are mapped by elevation zone, as percent of snow cover of the basin.

Other work has employed DEM data of Glacier National Park to study the effects of snow on vegetation and animal habitats. Allen and Walsh (1993) used digital elevation model (DEM) and Landsat multispectral scanner (MSS) data to study the dynamics of snow cover in different elevation zones. The spatial pattern and temporal persistence of snow at different elevation zones was found to influence vegetation growth.

Study Area

Glacier National Park is located in northwestern Montana. The terrain is rugged with some mountain peaks having elevations >3000 m. The mountains within the park are part of the Rocky Mountain cordillera. Much of the park is heavily forested with the predominant tree species in the area being evergreens (fir, pine and spruce). The Continental Divide runs in approximately a north-south direction through the park. The climate is generally harsher and drier east of the Continental Divide as compared to west of the Continental Divide.

About 50 glaciers and many permanent snow fields exist in the park. Snow covers high mountain areas 8-10 months of the year and much of the rest of the park for about 6 months of the year.

Data and Techniques

The Landsat TM scene (i.d.#5256917454) from 14 March 1991 (Fig. 1) is used for this study. DEM data with a spatial resolution of 30 m and 1-m (+/-15 m) increments in elevation are also used. The DEM data, acquired from the U.S. Geological Survey, were received as tapes of individual 7.5 X 7.5-minute scale topographic sheets. Individual segments of the DEM data were then digitally "stitched" together, providing coverage of much of the park. The DEM data were digitally registered to the TM data; the TM data represent the 'master' or base map.

Using an algorithm we call SNOMAP, the snow-covered area in the 14 March 1991 TM scene was mapped. A normalized difference snow index (NDSI) is the basis for the algorithm (Riggs and others 1994; Hall and others in press). The NDSI uses reflectances calculated from TM bands 2 and 5 as shown below, where TM band 2 (0.52-0.60 mm) is in the visible part of the spectrum, and TM band 5 (1.55-1.75 mm) is in the short-wave infrared part of the spectrum (Dozier 1989).

$$NDSI = (TM2-TM5) / (TM2+TM5) \qquad [1]$$

In order to determine the surface area covered after the DEM data were registered to the TM data, a program on the Silicon Graphics Inc. (SGI) workstation, Easi-Pace, was utilized. This program is called the Pace Terrain Analysis Package, and a description may be found in the PCI User's Manual Version 5.2 (PCI, 1993). Only the areas determined by SNOMAP to be snow covered were mapped as snow.

During the week of 10 March 1991, field measurements were acquired in Glacier National Park and an aircraft overflight was flown in support of a related study which was conducted to measure snow reflectance on the ground and from aircraft and satellite platforms (Hall and others 1993). Measurements and observations were also made of snow cover and depth during the field-study period.

Results

Field observations revealed that the entire area west of the Continental Divide was snow covered on and during at least the five days prior to and including 14 March 1991. In a meadow on the western side of the park, the average snow depth was about 78 cm. The area to the east of the Continental Divide in Glacier National Park was generally covered with thin snow, but there were patches of snow-free ground. In a flat area on the eastern side of the park, the average snow depth was about 11 cm.

The SNOMAP algorithm was applied to the TM scene; results showed that 34 percent of the scene (or, 10,670 km2 out of 31,688 km2) was snow covered. Actually, there was considerably more snow cover present than was mapped because of several factors. Snow exists on the flanks of the mountains; the true snow extent on these slopes cannot be mapped effectively unless topography is known. This is discussed in the next section and is the main topic of this paper. Additionally, dense forests cover much of the park, and though snow was present beneath the trees according to field observations, much of this snow is not mapped because the dense forests masked out a signal from the underlying snow (Hall and others in press). Snow is not mapped beneath the clouds and in the deepest cloud and mountain shadows (though snow is mapped in many cloud and mountain shadows on this scene).

Corrections for topographic effects. To avoid the confusion of partially snow-covered areas, we focus this study on the area west of the Continental Divide which was fully snow covered. However, the fractional snow-covered area could be computed if the area were not completely snow covered. Figure 2a shows a subscene from the 14 March 1991 TM scene of an area near and including part of Lake McDonald, the largest lake in Glacier National Park. Figure 2b shows results of the SNOMAP algorithm as applied to the area shown in 2a. The area has a topographic range of 2120 m. To illustrate the fact that there is considerable snow cover on the mountain slopes, Figure 3 shows a 10 times exaggeration of the area shown in Figure 2a after the DEM data were registered to the TM data.

The amount of snow cover mapped in the subscene was 215 km2, before the DEM data were registered to the TM data. After the TM and DEM data were registered, the total snow-covered area was found to be 1062 km2. Almost 5 times more snow is measured on the TM/DEM-registered data of this area as compared to when the TM data are used alone. This is because snow on the slopes of the mountains is accounted for when DEM and TM data are registered. Errors due to obscuration of snow cover by forests and clouds are not accounted for.

Topographic Correction Model. A simple model has been developed to describe the ruggedness of the topography of the 14 March 1991 TM scene so that such information can be used to calculate a correction factor which may be applied when using TM data alone to map snow in other parts of the scene in which DEM data are not available.

First, a relationship is established between topographic relief and the amount of correction necessary to adjust the TM-derived results for the effects of topography in mountainous terrain for determination of a more accurate snow-covered area. The ratio of the actual snow-covered area, Aa (as determined using the TM and DEM data together), to the area derived using TM data alone, AL, is used to calculate a correction factor, C, for each grid cell,

$$C = Aa / AL \qquad [2]$$

To establish the relationship, 60 areas or grid cells, were selected from all parts of the TM scene in which DEM data were registered. Each of these grid cells is 32.49 km2 in area (200 X 200 TM pixels). C was calculated or each of the 60 grid cells. A relationship was then established between C and an index of topographic relief, R, which is determined by taking the difference between the highest and lowest elevations within each of the 60 areas. R represents an approximation of the relief within each area. For the study area the following linear relationship was established,

$$C = 0.00381 R - 2.08786 \qquad [3]$$

where $900 \text{ m} < R < 1900 \text{ m}$

Using this information, the actual snow-covered area can be determined with an accuracy of +/- 0.4, for any area within the scene whether or not it is registered to the DEM as long as R can be determined from a topographic map.

Estimate of Actual Snow Cover. In order to calculate a topographic correction factor for a 974 km2 subscene in Glacier National Park (Fig. 5), the subscene was first divided into 30 grid cells. For each grid cell, C was calculated according to Eq.[3]. The actual area for the subscene was calculated by:

$$Aa = \sum_{i=1}^{30} AL * C \qquad [4]$$

and, for the area shown in Figure 5, the actual snow-covered area was 2967 km2. Thus there was actually about 3.05 times the amount of snow in the subscene than was mapped using TM data alone.

Theoretical Example. Theoretically, the surface area of a regular pyramid can be determined and compared to its base alone to demonstrate how much greater the surface area of a regular pyramid is, compared to the area of its base. To calculate the lateral or surface area of a regular pyramid, ALat, the following equation is used:

$$ALat = 1/2 \, nal \qquad [5]$$

where n is the number of sides of the base, a is the length of one side of the base, and l is the slant height of the pyramid. We chose an example that is realistic in terms of the relief in our study area: the theoretical area has a relief of 604 m, with a base of 10 TM pixels per side (an area of 81,225 m2 for the base of the pyramid). The slant height is 621 m, and ALat is 353,970 m2. The ratio of the lateral area of the regular pyramid to the area of the base of the regular pyramid is 4.36. Figure 6 is a schematic diagram (not drawn to scale) which illustrates this concept.

Errors. Errors are inherent in any method of measuring actual snow-covered area remotely. There are errors in the algorithm used to measure snow cover (see Riggs et al. 1994 and Hall et al. in press), primarily due to clouds and the inability to map snow cover in densely-forested areas.

The additional errors inherent in the calculation of actual snow-covered area using DEM data registered to TM data are due to several factors. The registration of the DEM data to the TM data may not be exact especially if there are few 'control points,' i.e. stable tie points in common between the two data sets. This is a potential source of error. The accuracy of the DEM is another factor that could introduce error as is the accuracy of the program (Pace Terrain Analysis Package) used in calculating surface area. Nevertheless, results appear to be realistic in terms of the terrain of Glacier National Park, as evidenced by the theoretical example shown above.

Discussion and Conclusion

In this paper we have discussed one of the major sources of error encountered in mapping actual snow-covered area from a 14 March 1991 TM scene in northwestern Montana.
The mapping of snow cover on mountain slopes using TM data alone introduces a significant error, underestimating the amount of actual snow-covered area mapped by more than 5 times for the highest-relief areas within the TM scene.

A simple model has been developed to describe the relationship between topographic relief and the correction needed to determine actual snow-covered area for the 14 March 1991 TM scene. A correction factor may be applied to measurements using TM data alone in order to account for snow cover on mountain slopes. The linear relationship that has been established is valid for only the TM scene used in this analysis; a new relationship would need to be established in order to use this model in another area.

Future refinements to this model include use of average slope instead of an index of topographic releif. This may permit a universally-applicable correction factor to be determined.

This technique for mapping surface area using DEM data, registered to satellite data, is applicable to non-snow-covered areas as well. It simply allows one to account for the relief of the terrain when doing calculations of surface area coverage. Another obvious application of this model is in forest-cover mapping.

In the future, the accuracy of the global snow-cover products, produced using MODIS data, will be improved using techniques similar to those described herein. The large difference in snow-covered area mapped, in some mountainous regions, using TM data alone versus using DEM data registered to TM data, illustrates the importance of employing a DEM globally.

A model similar to the one shown herein may be used in basins for which accurate prediction of runoff is crucial for apportionment of water resources. While snow is currently mapped by elevation zone in key basins, which allows one to calculate percent of snow-covered area, (Carroll 1990), our method represents a very simple, alternative way to measure actual snow-covered area or percentage of snow-covered area. In the future as more DEM data become available, techniques such as this will be pertinent to any number of other applications as well as the measurement of snow-covered area.

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Figures

1 Landsat thematic mapper (band 2 (0.52-0.60 µm)) scene (i.d.#5256917454) from 14 March 1991 covering northwestern Montana including Glacier National Park. The largest lake in the park, Lake McDonald (at arrow), can be seen in the south-central part of this scene.

2 a. Landsat false-color sub-scene showing part of Lake McDonald (at arrow) and surrounding area.
b. Same area as shown in 2a, but after SNOMAP was run to map the snow. Note that the forested areas to the east of Lake McDonald were snow covered according to field measurements, but snow was not detected by the algorithm.

3 Same area as shown in Figure 2a, but after the digital elevation model (DEM) data were registered to the TM data. Snow on the mountain slopes is visible; exaggeration is 10:1.

4 Relationship between topographic relief in each 200 X 200 pixel (32.49 km2) test area, and correction factor used to correct TM data for topographic effects.

5 Contour lines from a 974 km2 area within Glacier National Park, Montana in which digital elevation data were registered to Landsat TM data.

6 Schematic showing a theoretical example of the difference in surface area of the base of a regular pyramid as compared to the the lateral area of a regular pyramid; "a" is the length of one side of the base and "l" is the slant height of the pyramid. An example is taken from a sample area in Glacier National Park, Montana, where the relief was 604 m and the base of the pyramid was (285)2.